CIVIL ENGINEERING

INDIANA
DEPARTMENT OF HIGHWAYS

JOINT HIGHWAY RESEARCH PROJECT

FHWA/IN/JHRP-86/16 -2

Final Report Executive Summary

DESIGN OF REINFORCED EMBANKMENTS

Dana Norman Humphrey

PURDUE UNIVERSITY

JOINT HIGHWAY RESEARCH PROJECT

FHWA/IN/JHRP-86/16 -2

Final Report Executive Summary

DESIGN OF REINFORCED EMBANKMENTS

Dana Norman Humphrey

EXECUTIVE SUMMARY

Final Report

DESIGN OF REINFORCED EMBANKMENTS

TO:	H. L. Michael, Director Joint Highway Research Project	DATE:	October 14, 1986
		PROJECT:	C-36-36Q
FROM:	R. D. Holtz, Research Engineer Joint Highway Research Project	FILE:	6-14-17

Attached is the Final Report on the HPR Part II research study entitled "Design of Reinforced Embankments." This report completes all of the tasks of the approved work plan. The author of the report is Mr. Dana N. Humphrey who worked under my supervision.

The study indicates the usefulness of the relatively simple cap-type elastic-plastic work hardening soil behavioral model for the analysis and design of reinforced highway embankments. The primary benefit of the reinforcement is to reduce the shear stresses in the foundation near the toe of the embankment. Reinforcement was also found to be very beneficial for cases in which existing embankments must be widened and their grades raised. The assumptions of common limiting equilibrium design methods for reinforcement were also examined. The report includes a thorough summary of reinforced embankment case histories, as well as procedures to obtain model input parameters from the results of standard soils tests.

Copies of the report will be submitted to the IDOH and FHWA for their review. I look forward to receiving their comments on our research.

Sincerely yours,

Robert D. Holtz

R. D. Holtz, Ph.D., P.E.
Research Engineer

RDH/kr
Attachment
cc: A. G. Altschaeffl, J. M. Bell, M. E. Cantrall, W. F. Chen, W. L. Dolch, R. L. Eskew, J. D. Fricker, D. E. Hancher, R. A. Howden, M. K. Hunter, J. P. Isenbarger, J. F. McLaughlin, K. M. Mellinger, R. D. Miles, P. L. Owens, B. K. Partridge, G. T. Satterly, C. F. Scholer, K. C. Sinha, C. A. Venable, T. D. White, L. E. Wood

EXECUTIVE SUMMARY

Final Report

DESIGN OF REINFORCED EMBANKMENTS

by

Dana Norman Humphrey
Graduate Instructor in Research

Joint Highway Research Project

Project No.: C-36-36Q

File No.: 6-14-17

An Investigation Conducted by

Joint Highway Research Project
Engineering Experiment Station
Purdue University

in cooperation with the

Indiana Department of Highways
and
U.S. Department of Transportation
Federal Highway Administration

The contents of this report reflect the views of the author who is responsible for the facts and the accuracy of the data presented herein.

Purdue University
West Lafayette, Indiana
October 14, 1986

TECHNICAL REPORT STANDARD TITLE PAGE

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
FHWA/IN/JHRP-86/16		

4. Title and Subtitle	5. Report Date
EXECUTIVE SUMMARY DESIGN OF REINFORCED EMBANKMENTS	October 14, 1986
	6. Performing Organization Code
7. Author(s) Dana Norman Humphrey	8. Performing Organization Report No. JHRP-86-16
9. Performing Organization Name and Address Joint Highway Research Project Civil Engineering Building Purdue University West Lafayette, IN 47907	10. Work Unit No. 11. Contract or Grant No. HPR-1(24) Part II
12. Sponsoring Agency Name and Address Indiana Department of Highways State Office Building 100 North Senate Avenue Indianapolis, IN 46204	13. Type of Report and Period Covered Final Report 14. Sponsoring Agency Code

15. Supplementary Notes

Prepared in cooperation with the U.S. Department of Transportation, Federal Highway Administration. Study entitled "Design of Reinforced Embankments."

16. Abstract

A study was made of reinforced embankments constructed on undrained soft foundations using the finite element (FE) method with a cap elastic-plastic work hardening soil behavior model. A straightforward procedure was developed to obtain the cap input parameters from standard soil test results. The FE analyses showed that crust strength and foundation compressibility have the greatest influence on the benefit possible with reinforcement. The main effect of the reinforcement is to reduce shear stresses in the foundation near the embankment toe. Reinforcement was found to be very beneficial for widening and raising the grade of existing embankments.

Underlying assumptions of modified limiting equilibrium methods were examined. The assumption of no change in normal stress on the portion of the slip surface passing through the fill due to reinforcement appears to be valid. In addition, a thorough summary of reinforced embankment case histories was presented and evaluated.

17. Key Words	18. Distribution Statement
Embankments, reinforcement, geotextiles finite element method, weak foundations design analysis, limiting equilibrium, settlements, embankment widening	No restrictions. This document is available to the public through the National Technical Information Service, Springfield, Virginia 22161

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	423	

Form DOT F 1700.7 (8-69)

EXECUTIVE SUMMARY

INTRODUCTION

Tensile reinforcement is being used more frequently to increase the end of construction stability of embankments founded on soft soils. It allows embankments to be constructed to greater heights or with steeper side slopes, or in some cases reinforcement enables staged construction to be avoided. In a typical application, the reinforcement is placed at the base of the embankment, and geotextiles or geogrids are commonly used as the reinforcing material.

Suitable procedures for designing reinforced embankments are still being developed and all suffer from the limitations that are inherent for any design methods for embankments on soft ground. Modifications of existing limiting equilibrium techniques are presently the most common, but they make several assumptions that have not been confirmed either by research or documented case histories.

Deformations are one of the important factors in reinforced embankment behavior since they control the force which develops in the reinforcement. Finite element analysis have been used to gain insight into the deformations and resulting embankment behavior, and some of these analyses are described in the Report. Recent work as part of this research (McCarron, 1985) suggested that the so-called "cap" soil plasticity behavioral model could be used to represent behavior of soft foundation soils, but a trial and error procedure was required to obtain the cap parameters.

OBJECTIVES OF THE RESEARCH

The first objective was to develop a straightforward and reliable procedure to determine the cap model parameters from standard soil test results and to investigate the capabilities and limitations of the model to predict undrained soil behavior. This would allow the model to be used by IDOH engineers with greater simplicity and understanding for the analysis of embankments constructed on soft ground.

The second objective was to identify the range of soil properties and embankment geometries where reinforcement is most beneficial, and thereby to gain insight into the factors which contribute to the increase in stability. Special attention was given to widening and raising the grade of existing embankments, because these problems are important to IDOH in upgrading existing facilities. This objective was met by using a finite element analysis technique together with the cap soil behavioral model. The study was limited to undrained foundation conditions, as they are the most critical for design.

The final objective was to examine the validity of some of the assumptions of modified limiting equilibrium analysis methods. Thus, the proper roles of finite element and limiting equilibrium analyses in current design practice could be established.

ORGANIZATION OF THE REPORT

This Report has four main parts. The first part, Chapter 2, reviews the available literature on design of reinforced embankments. The review covers applications of both finite element and limiting equilibrium methods. In addition, a thorough summary of reinforced embankment case histories is presented.

The second part of the report describes the development of a straightforward procedure to determine the cap model parameters from standard soil test results. The main features and governing equations of the model are reviewed in Chapter 3, and the procedure is developed in the first few sections of Chapter 4. This is followed by application of the model to some available laboratory test results. Then, the cap parameters for 52 clayey soils are summarized. Finally, the effect of varying the input soil properties on predicted stress-strain and pore pressure response is examined

The third part of the Report, Chapter 5, involves the use of a plane strain finite element program with the cap soil model to make a comparative study of reinforced and unreinforced embankment behavior. This is followed by a study of the effect of embankment geometry and foundation soil properties on embankment behavior. The method is applied to widening and raising the grade of existing embankments in Chapter 6.

In the last part, Chapter 7, limiting equilibrium analysis techniques are examined and some of their underlying assumptions are reassessed in light of results from the finite element studies. The use of finite element and limiting equilibrium analyses for embankment design is also discussed.

In the following, each of these parts is summarized in some detail.

PART ONE (CHAPTER 2): A LITERATURE REVIEW OF REINFORCED EMBANKMENTS

In this chapter, a review of the large volume of available literature related to reinforced embankments is made. First, limiting equilibrium analyses were examined, followed by a review of finite element analyses of reinforced embankments. A comprehensive summary of reinforced embankment case histories is also presented in the Report.

The most common method used in current design practice are slope stability methods. The methods assume that the normal stress on the failure surface is unchanged and that the presence of the reinforcement does not affect the frictional resistance provided by granular material. For circular failure surfaces there is considerable controversy whether the reinforcing force should be in the original direction of the reinforcement, generally horizontal, or tangent to the slip circle. This latter assumption yields a significantly higher calculated factor of safety.

Bearing capacity methods that include the effect of increasing strength with depth and limited thickness of soft foundation soils were reviewed and their applicability to analysis of reinforced embankments is discussed in the Report. Sliding within the embankment, slipping on the embankment fill-reinforcement interface, and lateral splitting were also identified as potential failure modes.

The three limiting equilibrium type procedures for design of reinforced embankments reviewed differ in detail, but in general they employ similar analysis methods. The main difficulty in applying any of the procedures is in estimating the allowable force in the reinforcement.

Finite element procedures for modeling reinforced embankment behavior are also described in the Report. Because incremental construction and large deformations must be accounted for in the analysis, elastic-plastic models such as the cap model appear to give the most realistic representation of embankment and foundation soil behavior.

Results from the analyses show that reinforcement reduces shear stresses and lateral deformations in the foundation soils and increases embankment stability. There is little effect on vertical settlements. Reinforcement also reduces tensile strains in the embankment. The benefit from reinforcement increases as the strength of the foundation decreases and the reinforcement modulus increases.

The FEM analyses performed for this present research addresses some of the limitations of previous studies. Most of the previous studies did not consider the effect of a dried surface crust or increasing strength and modulus with depth in the foundation soils.

The data from the 40 cases summarized in the Report can be used as a guide for preliminary designs and as a basis of comparison for new analysis techniques. They are summarized in a concise format to allow easy identification of cases most pertinent to a particular problem.

The cases had several characteristics. Foundation materials were typically soft organic soils with a shear strength of less than 15 kPa (300 psf) underlain by a stronger layer. In many cases it was necessary to combine reinforcement with other special measures such as wick or sand drains, staged construction or berms to maintain an acceptable safety factor. Reinforced embankments were observed to fail by excessive elongation of low modulus reinforcement, tensile failure of the reinforcement, and pulling apart of joints or sewn seams between strips of reinforcement. Reinforcement was used for widening and raising the grade of existing embankments in 3 cases.

The height of reinforced embankments at failure was observed to be up to 2 m greater than predicted by conventional bearing capacity theory (see Fig. 2.15 -- copy attached). The explanation for this is open for discussion but may be that reinforcement enhances the beneficial effect that the following factors have on stability: limited thickness or increase in strength with depth of the soft foundation soils, the dried surface crust, flat embankment side slopes, or dissipation of pore water pressures during construction. It was shown that the bearing capacity of footings on soil with increasing strength with depth can partially account for the difference.

The bearing capacity factor (see Fig. 2.16 -- copy attached) for foundations of limited depth with full shearing resistance at the foundation-geotextile interface agreed well with the values observed at failure for two reinforced embankments.

PART TWO (CHAPTERS 3 and 4): CAP SOIL BEHAVIOR MODEL AND PROCEDURE FOR DETERMINING THE CAP PARAMETERS

The cap soil behavior model is a nonlinear elastic-plastic isotropic work-hardening plasticity model. It was developed from the classical incremental theory of work-hardening plasticity for materials which have time and temperature independent properties. In general, cap models describe the yielding behavior of soil

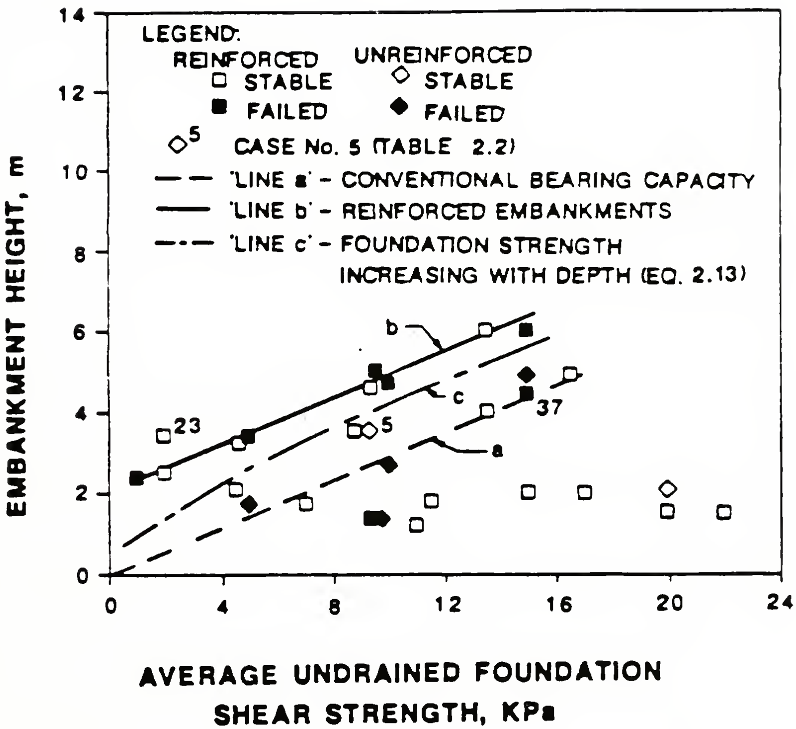

Figure 2.15 Reinforced and unreinforced embankment height vs. undrained shear strength of the foundation for the cases in Table 2.2.

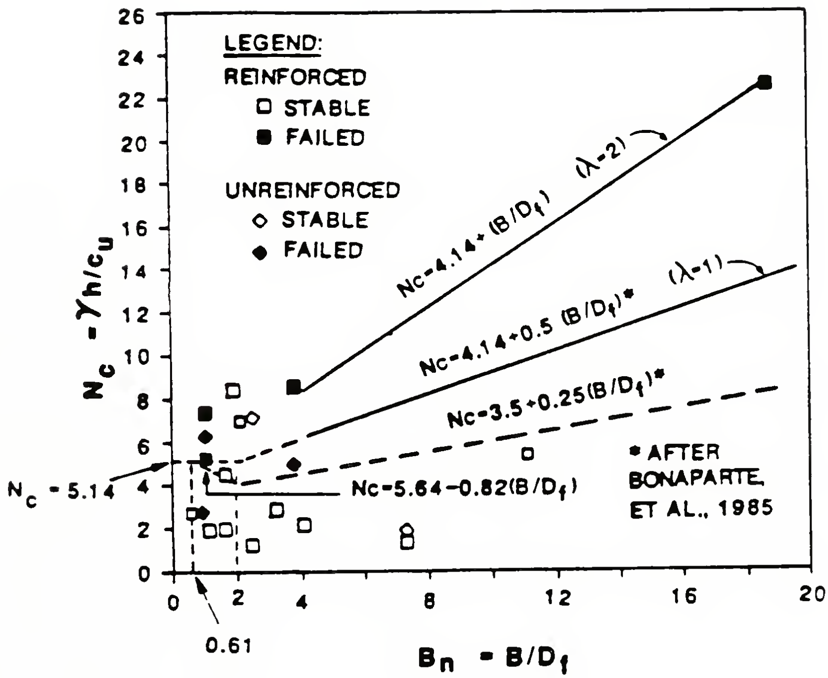

Figure 2.16 Relation between bearing capacity factor and normalized embankment width.

with an ultimate yield surface that is fitted with a movable end cap. Both the ultimate yield and cap surfaces are symmetric about the hydrostatic axis. The movement of the cap is controlled by the hardening and softening behavior of the soil which is expressed as a hardening law. For some versions of the cap model the ultimate failure surface is also allowed to move as controlled by a hardening law. Strains are elastic for stress changes that fall within the region bounded by the ultimate yield and cap surfaces, but they are elastic-plastic for stress changes on the surfaces.

The main features and governing equations for the cap soil behavior model and the elastic-plastic constitutive equation for loading on the cap are presented in Chapter 3.

In Chapter 4, a straightforward procedure for determining the cap parameters from the results of conventional soils tests, as developed in this research, is presented. Thus, one of the main obstacles to using the cap soil behavior model has been overcome. Table 4.1 (copy attached) is a summary of the required cap parameters. Input soil properties are given in Table 4.4 (copy attached). They can be obtained from conventional tests and the required computations can be done using a hand calculator.

Worked examples to illustrate the procedure are given in the Report. In addition, a procedure was presented for overconsoli-

Table 4.1
Summary of cap parameters.

Ultimate failure surface	
α	slope in $I_1'-J_2^{1/2}$ space
κ	intercept with $J_2^{1/2}$ axis
T_c	tension cut-off
Elastic behavior	
K_1	bulk modulus parameter
K_2	bulk modulus parameter
A_p	atmospheric pressure
G_1	shear modulus parameter
G_2	shear modulus parameter
Strain hardening	
D	hardening parameter
W	hardening parameter
Cap	
R	cap aspect ratio
x_o	initial position of cap
Initial stresses	
A_2	surcharge
γ	average unit weight of soil
$\hat{K}_o$	initial coefficient of lateral earth pressure
Pore pressure response	
β	factor for bulk modulus of fluid/solids

Table 4.4
Soil properties required to calibrate cap model.

ϕ'
c'
s_u/σ'_{vo}
C_c
C_r
ν'
e_o
γ_t for soil above water table
γ_{sub} for soil below water table
K_o

dated soils to determine the initial position of the cap which yields the correct undrained shear strength.

The procedure was used to determine the cap parameters for Boston Blue Clay using results from hydrostatic and K_o consolidated triaxial and plane strain tests. These parameters were then used in a computer program called CAP to calculate stress-strain curves, pore pressure response, and effective stress paths. Comparisons were made to observed test results. In general there was excellent agreement, except for a large discrepancy for pore pressures and effective stress paths in tests that underwent reversal of principal stress during shearing and tests on overconsolidated samples. The discrepancy is at least partially because our implementation of the cap model does not allow plastic volumetric strain for stress changes within the region bounded by the cap and ultimate failure surfaces.

Cap parameters were also calculated using CIU triaxial test results for 52 clayey soils. The summary can be used for guidance when selecting parameters for preliminary designs.

For proper predictions for cases with initial nonhydrostatic consolidation ($K_o \neq 1$), cap parameters must be calculated using strength data from nonhydrostatically consolidated tests.

A study of the effect of the input soil properties on calculated CIU triaxial behavior indicated that the results can be used for guidance if it is necessary to adjust the input parameters to obtain better agreement between predicted and observed behavior. s_u/σ'_{vo} was found to have the largest influence on predicted behavior.

PART THREE (CHAPTERS 5 AND 6): FINITE ELEMENT STUDY OF REINFORCED EMBANKMENT BEHAVIOR AND EMBANKMENT WIDENING

A comparative study between reinforced and unreinforced embankment behavior was made using a finite element analysis technique with a cap type soil plasticity behavior model. An embankment composed of granular fill was reinforced by a single layer of reinforcement placed at its base. A typical embankment construction sequence was simulated. The foundation soils were soft and no drainage was allowed during construction. The purpose of the study was to investigate the effect of reinforcement on deformations and stresses and to identify which aspects of embankment geometry and foundation properties had the greatest effect on behavior. A study of reinforcement applied to the important practical case of embankment widening was also carried out.

The height at failure, reinforcement force at failure, and relative increase in surcharge made possible by reinforcement for 15 cases are summarized in Table 5.11 (copy attached). Failure heights ranged from 2.8 ft for no crust to 11.3 ft for a strong crust. The relative increase in surcharge made possible by reinforcement ranged from 5 to 70%.

Table 5.11
Summary of results of analysis.

Base Width (ft)	Side Slope (h:v)	Fnd Depth (ft)	Crust Strength ---	Special Case ----	-Ht. at Failure- Unreinf. (ft)	Reinf. (ft)	Reinf. Force at Failure (k/ft)	Relative Increase in Surcharge
180	2:1	15	Strong		9.4	10.3	1.3	5%
180	2:1	15	Weak		6.6	8.4	1.6	15%
180	2:1	15	None		2.8	4.7	1.0	60%
180	2:1	30	Strong		8.4	11.3	1.5	7%
180	2:1	30	Weak		7.5	8.4	1.3	22%
180	2:1	30	None		3.8	6.6	1.7	70%
180	2:1	60	Strong		11.3	11.3	1.1	9%
180	2:1	30	Strong	(1)	8.4	8.4	1.4	22%
180	2:1	30	Weak	(1)	6.6	7.5	1.8	29%
180	2:1	30	None	(1)	2.8	2.8	0.6	50%
180	2:1	30	Strong	(2)	8.4	9.4	1.2	10%
180	2:1	30	Strong	(3)	8.4	8.4	0.9	12%
180	3:1	30	Strong		9.4	10.3	0.8	7%
180	3:1	30	None		3.8	6.6	1.1	53%
120	2:1	30	Strong		7.5	10.3	1.2	6%

Special Cases:
(1) Compressible foundation
(2) Weak pocket at toe
(3) Weak pocket beneath slope

Crust strength was found to be the most important factor governing embankment behavior. The heights at failure of both reinforced and unreinforced embankments decreased with crust strength. The beneficial effect of reinforcement increased significantly as the crust strength decreased. The results showed that a pocket of weak, normally consolidated soil in an otherwise strong crust had only a limited influence on embankment behavior and the benefit from using reinforcement was modest. The effect of foundation depth and embankment width was small. Reinforcement was slightly more beneficial for steeper side slopes and was very effective for compressible foundation soils.

Reinforcement increases the height at failure and reduces displacements in the foundation. The largest reduction occurs in the upper 10 ft of the foundation near the toe. It is logical that the properties of the soil in this zone (i.e. the crust) have the primary influence on embankment behavior. Reinforcement significantly reduces shear stresses in the foundation at the toe. The forces developed in the reinforcement were much less than its tensile strength. This indicates that the strength of the embankment fill and foundation soils are fully mobilized and failure occurs before there are sufficient deformations to develop the ultimate tensile strength of the reinforcement. Shear stresses at the soil-reinforcement interface were less than the interface strength so slip along this plane did not occur. The reinforcement beneath the embankment toe was unstressed.

Finally, the results of the present study are in general agreement with results reported by others.

As far as embankment widening is concerned, reinforcement has been used successfully in three field applications. It is believed that the reinforcement had a significant stabilizing effect but there was insufficient data to confirm this. Furthermore, no analytical studies have been made of the problem.

The behavior of existing embankments on soft foundations that are widened and have their grade raised was studied using PS-NFAP with the cap soil behavior model. Reinforcement had a significant beneficial effect especially for some combinations of existing embankment height, width of the widened section, and crust strength. In one case the relative increase in surcharge made possible by reinforcement was as high as 40%. The behavior of embankments with a 45-ft widened section approached that of a normal section constructed with horizontal lifts under undrained conditions. The benefit was less for a narrow, 15-ft widened section than for 30 and 45-ft widened sections. This is probably because the critical failure surface for the narrow section passed near the shoulder of the existing embankment, so the moment arm of the reinforcing force was small. The reinforcement was found to reduce the extent of the plastic zone in the foundation and to reduce the tensile zone in the embankment fill. Forces in the reinforcement were small near the embankment centerline so there may be little benefit to reinforcing the central portion of the existing embankment crest.

PART FOUR (CHAPTER 7): LIMITING EQUILIBRIUM METHODS

As mentioned earlier, limiting equilibrium methods which are modified to account for the stabilizing effect of reinforcement are the most common techniques currently used to design reinforced embankments. The methods generally assume that the reinforcement provides only a resisting force or moment but does not alter the normal stress on the assumed failure surface. Hence, the shear resistance provided by frictional materials is unchanged. All methods require an estimate of the allowable force in the reinforcement.

It was found that the failure heights and percent increase in failure height calculated with limiting equilibrium and FE methods are similar. However, greater increases have been observed for several case histories (Chapter 2). Comparison of stresses on critical slip surfaces for reinforced and unreinforced embankments showed that there is little effect on normal stresses in the fill; therefore, the assumption of the simplified Bishop method that the normal stress and resulting shear strength in the fill remains unchanged is valid. The comparison also showed that the main effect of the reinforcement was to reduce the shear stresses in the foundation near the toe of the critical circle. We suggest for the present that the reinforcing force be taken to act in the original direction of the reinforcement. However, caution is recommended when designing embankments on extremely weak foundations ($s_u < 125psf$).

The finite element method is best used to estimate the force in the reinforcement when the foundation soils fail and for comparative studies of reinforced and unreinforced embankment behavior. This is primarily because of the inability of cap to represent reversal of the principal stresses, which leads to overestimation of the height at failure. Limiting equilibrium methods have been calibrated to field experience (at least for unreinforced embankments), and they should be used to estimate the safety factor for design purposes.

CONCLUDING REMARKS

Finite element analyses using the cap soil plasticity behavior model have been applied to analysis of reinforced embankments constructed on soft ground. A procedure has been developed to determine the cap model parameters from standard soil test results. The analysis technique was applied to several embankment and foundation geometries with different soil properties to identify the situations where reinforcement is likely to be the most beneficial. Critical assumptions of limiting equilibrium analysis methods that are modified to include the effect of reinforcement have also been examined.

Finally, the Report presents a number of important conclusions and recommendations for further research on this important topic. A list of 214 references is appended.

COVER DESIGN BY ALDO GIORGINI